

Light sterile neutrinos in the early universe

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ν_s and cosmic radiation energy density

- Motivations and status
 - how much room for ν_s in the universe?
- Contribution to radiation energy density: suppression effects
 - Partial thermalization
 - Mass correction
- discussion

How much room for ν_s in the Early Universe?

MOTIVATION AND STATUS

Probing new light particles with cosmology

- Effective number of relativistic species:
 - in units of neutrinos: $N_{\text{eff}} = \frac{\rho_{\text{rel}} - \rho_{\gamma}}{\rho_{\nu}^{\text{th}}},$
 - Neutrino energy density $\rho_{\nu}^{\text{th}} = (7\pi^2/120)(4/11)^{4/3}T_{\gamma}^4$
- Standard Model: $N_{\text{eff}} = 3.046$
- Beyond the SM: *dark radiation*
 - $\Delta N_{\text{eff}} = N_{\text{eff}} - 3.046$
 - generally time dependent, non-integer

Measurements of N_{eff}

- Big Bang Nucleosynthesis (BBN)

- $T \approx 0.2 \text{ MeV}$

- New, higher ^4He mass fraction:

$$Y_p = 0.2565 \pm 0.0010(\text{stat.}) \pm 0.0050(\text{syst.})$$

Y. I. Izotov and T. X. Thuan, ApJ 710, L67 (2010)



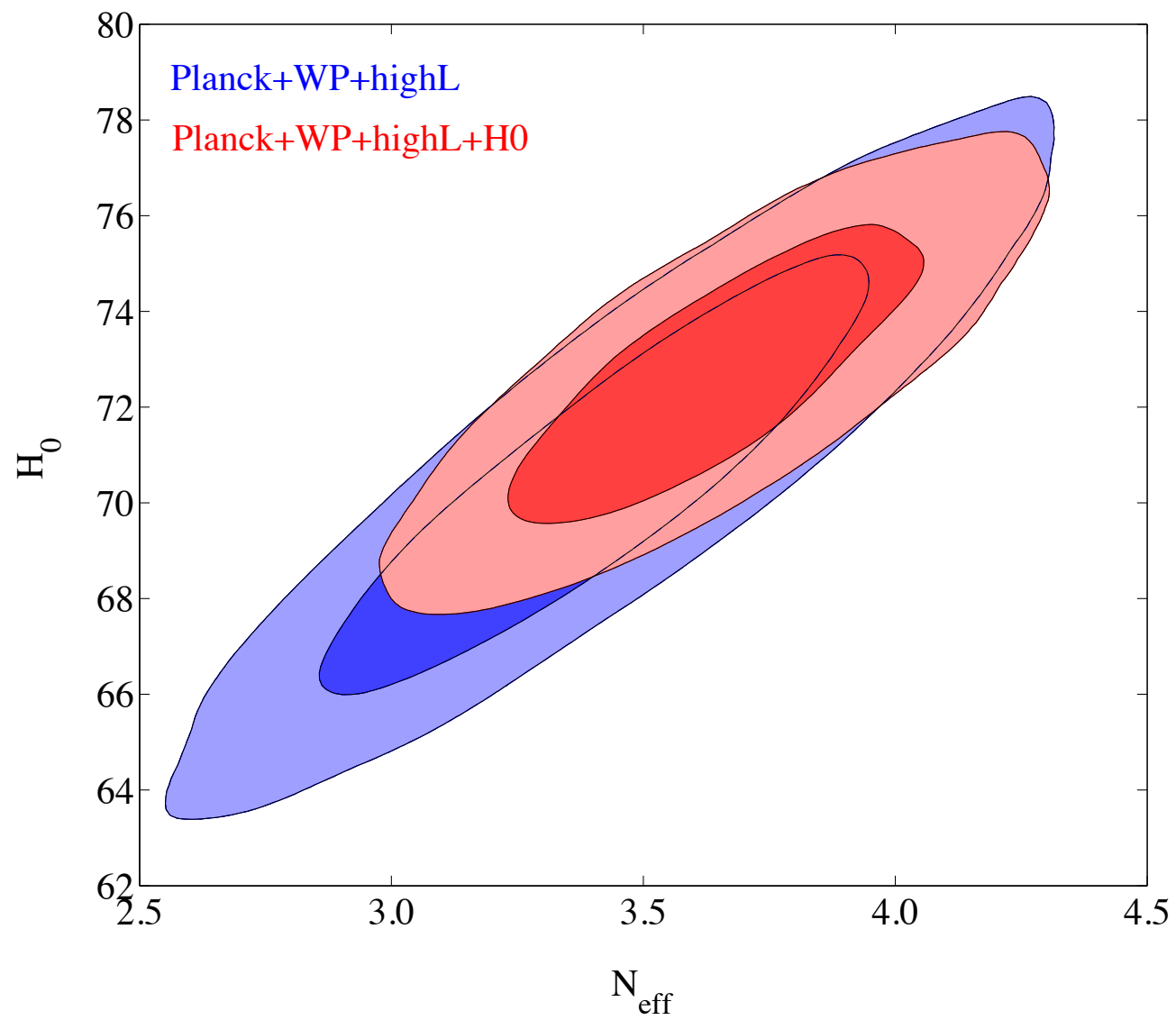
$$N_{\text{eff}}^{\text{BBN}} = 3.68^{+0.80}_{-0.70}$$

Aver, Olive, and Skillman, JCAP 1005, 003 (2010), JCAP 1204, 004 (2012),
Mangano and Serpico, Phys.Lett. B701, 296 (2011),
Nollett and Holder, (2011), arXiv:1112.2683

Measurements of N_{eff}

- Cosmic Microwave Background (CMB)
 - matter-radiation equality, $T_{\text{eq}} \approx 0.79 \text{ eV}$

| | |
|--------|---|
| Planck | $N_{\text{eff}}^{\text{CMB}} = 3.30 \pm 0.27$ |
| SPT | $N_{\text{eff}}^{\text{CMB}} = 3.71 \pm 0.35$ |
| WMAP9 | $N_{\text{eff}}^{\text{CMB}} = 3.84 \pm 0.4$ |
| ACT | $N_{\text{eff}}^{\text{CMB}} = 2.78 \pm 0.55$ |



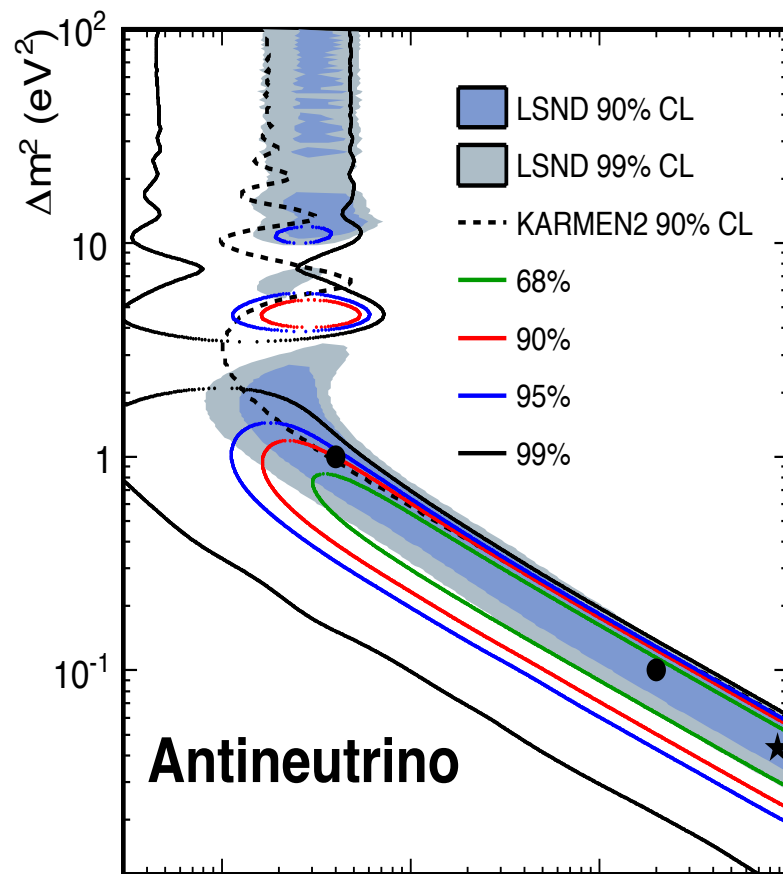
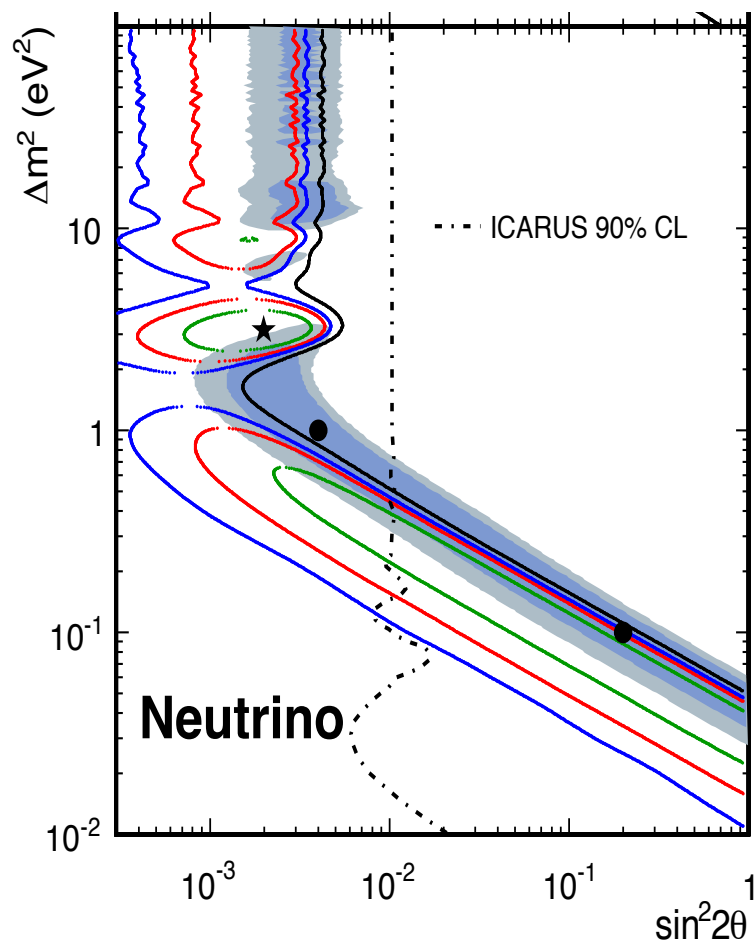
Archidiacono et al., arXiv:1307.0637

There is room for ν_s

- $N_{\text{eff}} > 3$ is allowed, or even favored
 - Depending on details of analysis
 - $N_{\text{eff}} = 4$ probably allowed, $N_{\text{eff}}=5$ probably excluded

Oscillation searches for ν_s

- LSND, MiniBooNE : claim of $\nu_\mu \rightarrow \nu_e$ *appearance*
 - Effective angle: $\sin^2 2\theta_{\mu e} \equiv 4|U_{\mu 4}U_{e 4}|^2$
 - Tension with negative results: Icarus, Karmen, E776, Nomad
 - Tension between ν_e and anti- ν_e MiniBooNE data sets

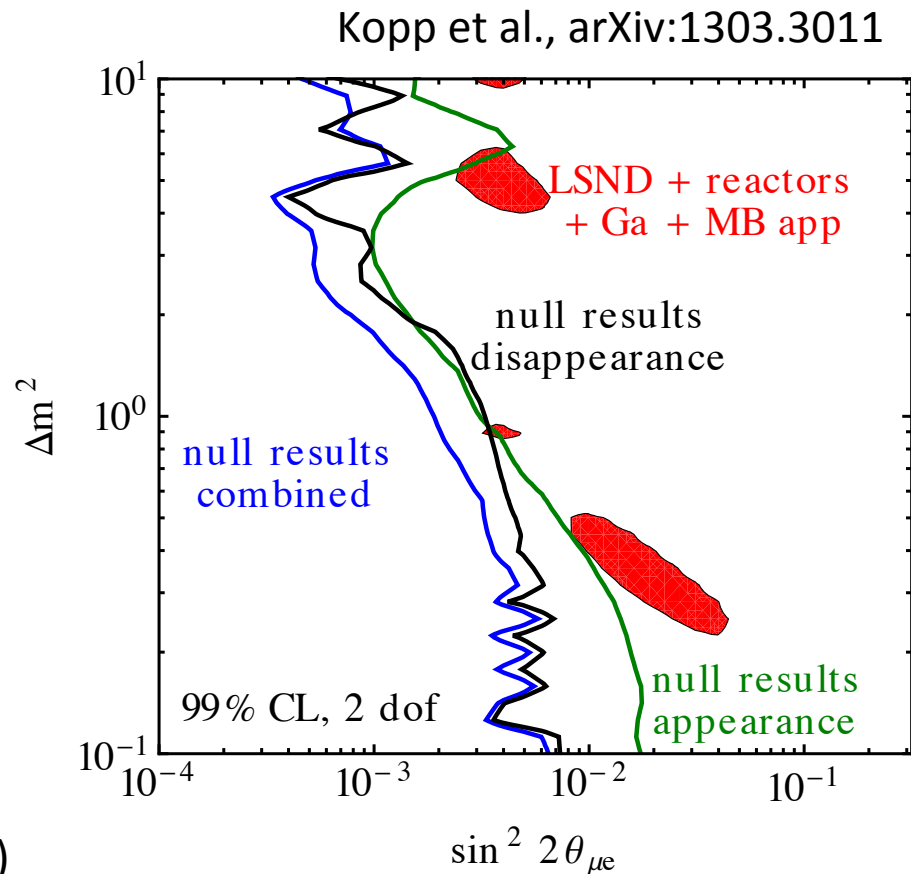


Aguilar-Arevalo et al., arXiv:1303.2588

Other hints of ν_s

- Reactor anomaly
 - anti- ν_e disappearance
- Gallium anomaly
 - ν_e disappearance

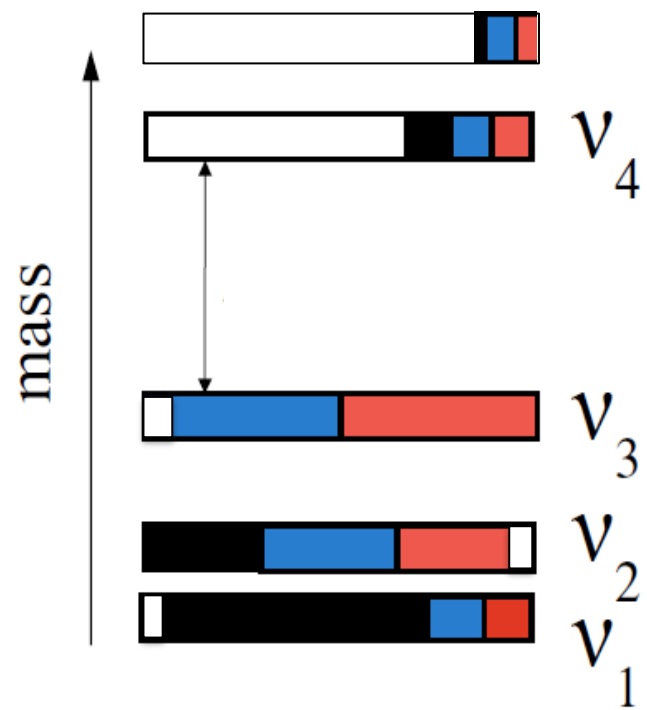
Mueller et al., PRC83, 054615 (2011)
Mention et al., PRD83, 073006 (2011)
Giunti and Laveder, PRC83, 065504 (2011)
Kaether, et al., PLB685, 47 (2010),
Abdurashitov et al. PRC80, 015807 (2009)



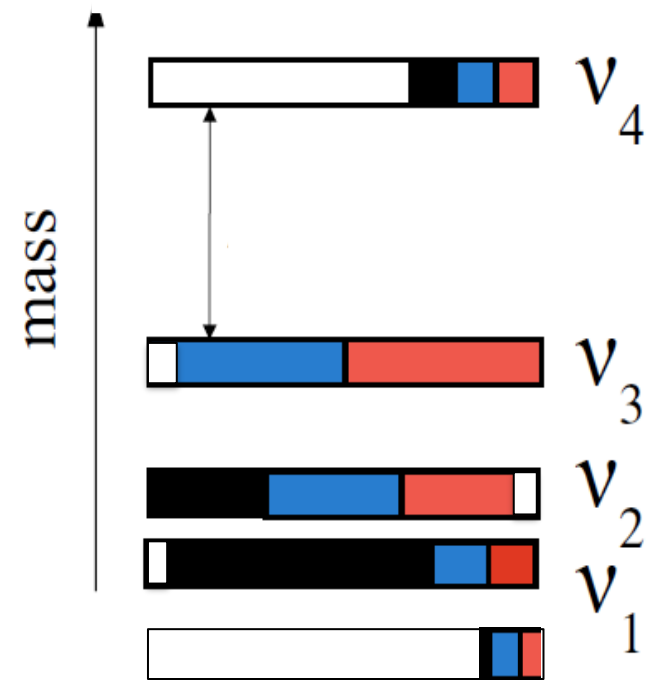
How many light ν_s ?

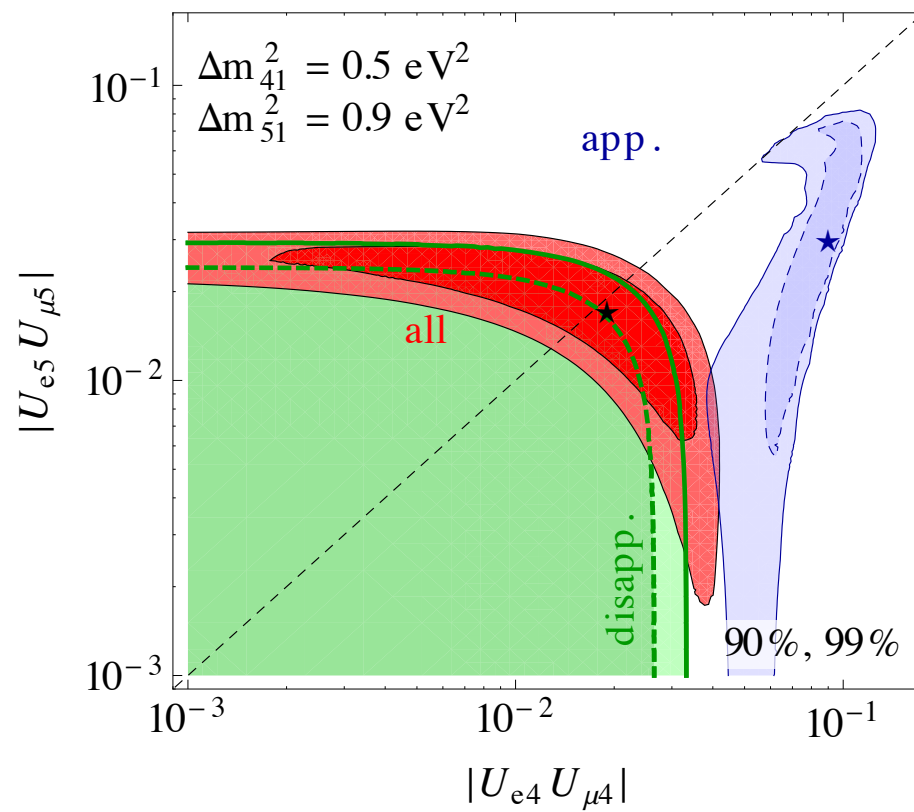
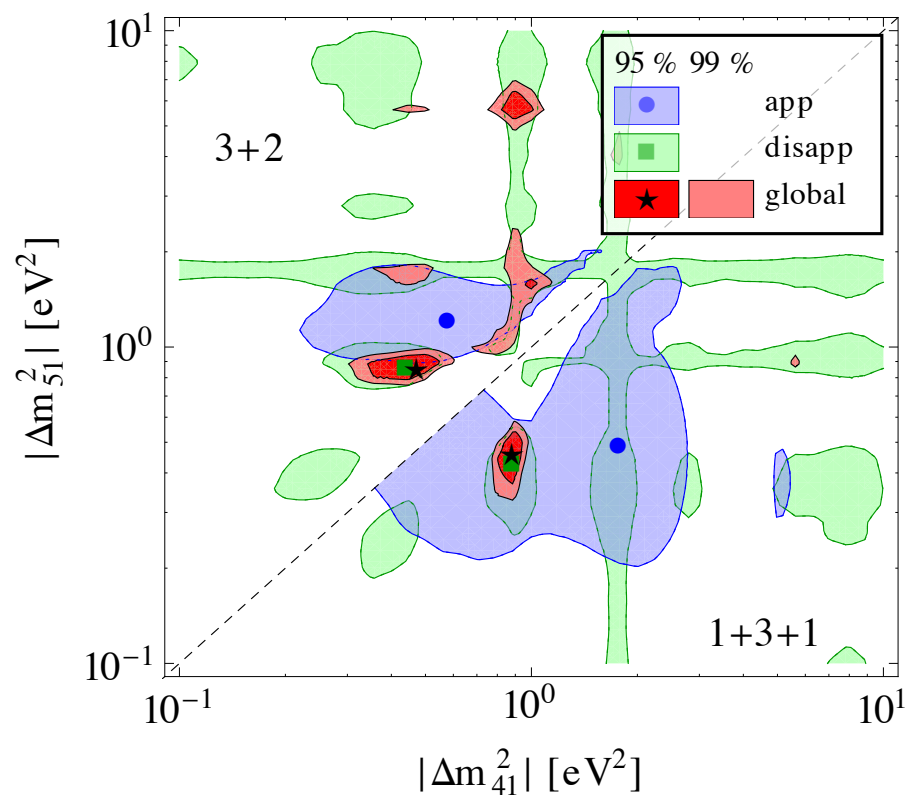
- $3 + 1$ (1 sterile)
 - Minimal model, fits well MB ν and MB anti- ν data separately
 - Poor fit of MB ν and MB anti- ν data combined
- $3 + 2$ (2 sterile)
 - Allows CP violation
 - Favored by MB ν and MB anti- ν data combined

3 + 2



1 + 3 + 1

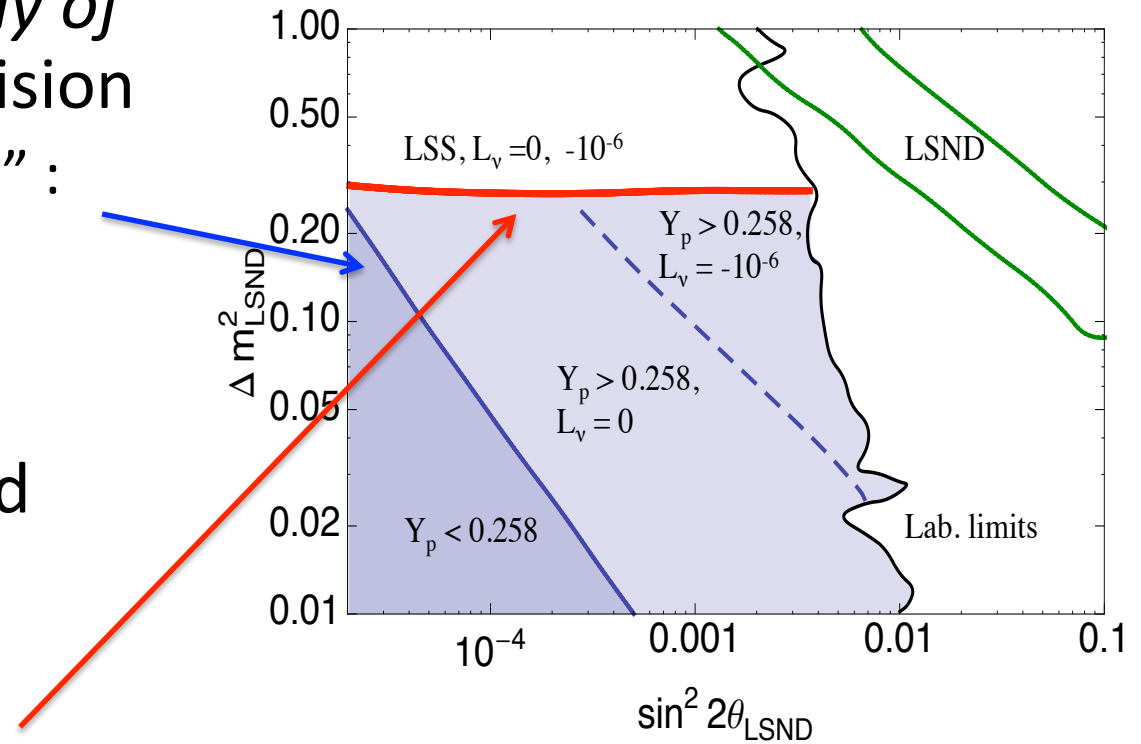




Kopp et al., arXiv:1303.3011, Giunti and Laveder, PRD84, 073008 (2011)

Contribution of ν_s to N_{eff}

- Production: *interplay of oscillations and collision*
 - “thermalization line” : production rate \approx Hubble rate
- $3 + 1 : \nu_s$ thermalized
 - $N_{\text{eff}} = 4$
 - Constrained by cosmological mass bound



Cirelli et al., Nucl.Phys. B708 (2005) 215-267

Chu and Cirelli, Phys.Rev. D74 (2006) 085015

LM Krauss, C.L. & C. J. Smith, arXiv:1009.4666

3+2 : richer phenomenology

T. Jacques, L. Krauss, C.L., Phys. Rev. D 87, 083515, arXiv:1301.3119

- Incomplete thermalization
 - important to assess tension between SBL and dark radiation bounds
 - Lessens tension with cosmological mass bound
- At least 1 mildly relativistic at T_{eq}
 - Suppressed contribution to $N_{\text{eff}}^{\text{CMB}}$

References

S. Dodelson, A. Melchiorri, and A. Slosar, Phys.Rev.Lett. 97, 041301 (2006)

J. Birrell, C.-T. Yang, P. Chen, and J. Rafelski, (2012)

S. Joudaki and M. Kaplinghat, Phys.Rev. D86, 023526 (2012)

R. Foot and R. R. Volkas, Phys. Rev. Lett. 75, 4350 (1995).

P. Di Bari, P. Lipari, and M. Lusignoli, Int.J.Mod.Phys. A15, 2289 (2000)

K. Abazajian, G. M. Fuller, and M. Patel, Phys. Rev. D64, 023501 (2001)

R. Foot and R. R. Volkas, Phys. Rev. D55, 5147 (1997)

Melchiorri et al., JCAP 0901, 036 (2009)

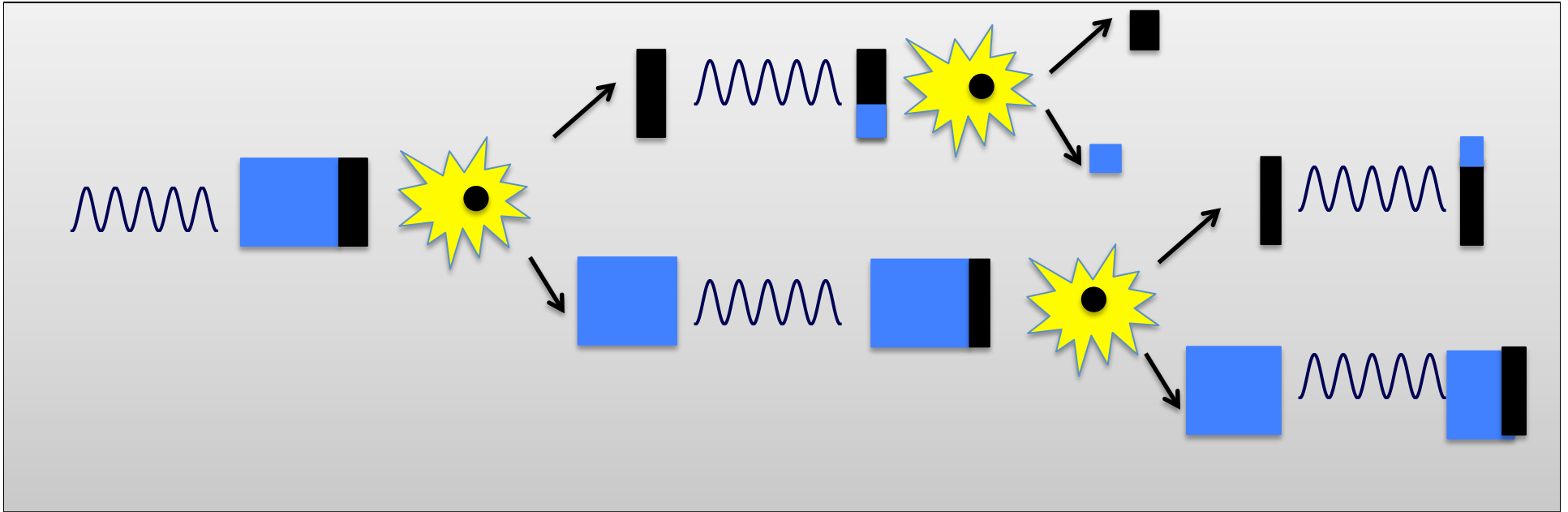
Partial thermalization

Mass correction

CONTRIBUTION TO RADIATION DENSITY: SUPPRESSION EFFECTS

PARTIAL THERMALIZATION

Growing a v_s population



- Quantum measurement
 - Collisions break the coherence of the wavepackets
 - v_s can accumulate and reach thermal abundance

Neutrino scattering

- Coherent : oscillations
 - Zero lepton asymmetry

$$V_\alpha = -A_\alpha \frac{2\sqrt{2}\zeta(3)}{\pi^2} \frac{G_F T^4 p}{m_W^2} \quad A_e = 17 \text{ and } A_{\mu,\tau} = 4.9$$

$$\sin^2 2\theta_{\alpha s} \simeq 4U_{\alpha 4}^2 U_{s4}^2 \simeq 4U_{\alpha 4}^2, \quad \alpha = e, \mu$$

$$\sin^2 2\theta_m \simeq \frac{\sin^2 2\theta_{\alpha s}}{(1 - b_\alpha(p, T))^2} \quad b_\alpha(p, T) = \frac{2E V_\alpha}{\Delta m^2}$$

- Incoherent: collisions

$$\Gamma_\alpha \simeq y_\alpha \frac{180\zeta(3)}{7\pi^4} G_F^2 T^4 p, \quad y_e = 3.6, \quad y_{\mu,\tau} = 2.5.$$

Production rate

- Assuming $\Gamma_{\text{osc}} \ll \Gamma_{\text{mfp}}$

$$\left(\frac{\partial}{\partial t} - H E \frac{\partial}{\partial E} \right) f_s(E, t) = \underbrace{\frac{\sin^2 2\theta_m(E, t)}{2}}_{\text{Avg. oscillation probability}} \underbrace{\frac{\Gamma_a(E, t)}{2}}_{\text{Collision rate}} (f_\alpha(E, t) - f_s(E, t))$$

- “thermalization line” :

$$\frac{\sin^2 2\theta_m(E, t)}{2} \frac{\Gamma_a(E, t)}{2} \approx H = \sqrt{\frac{4\pi^3 g^*}{45}} \frac{T^2}{M_{\text{pl}}}$$

Analytical solution: f_s at decoupling

- Assume:
 - ν_s mixed with ν_μ and ν_e
 - g^* constant, f_α constant, $b_\alpha \ll 1$ at freeze-out

- Result:

$$\frac{f_s}{f_\alpha} \simeq 1 - \exp \left[-6.51 \times 10^2 \left(\frac{m_4}{eV} \right) (U_{e4}^2 + 1.29 U_{\mu 4}^2) \right]$$

- f_s/f_α momentum-independent
- generalized to 3+2 (if 2 steriles don't mix)

Dodelson and Widrow, PRL. 72, 17 (1994), Foot and Volkas, PRD, 5147 (1997)

Numerical solution for 3+2

$$\dot{\rho} = \mathcal{H}\rho - \rho\mathcal{H}^\dagger = -i[H_m + V_{\text{eff}}, \rho] - \left\{\frac{\Gamma}{2}, (\rho - \rho_{eq})\right\}$$

$$\left(\frac{\partial \rho}{\partial T}\right)_{\frac{E}{T}} = -\frac{1}{HT} \left(-i[H_m + V_{\text{eff}}, \rho] - \left\{\frac{\Gamma}{2}, (\rho - \rho_{eq})\right\} \right)$$

$$H_m = U H_0 U^\dagger$$

$$H_0 = \text{diag}(E_1, E_2, E_3, E_4, E_5)$$

$$V_{\text{eff}} = I(V_e, V_\mu, V_\tau, 0, 0)$$

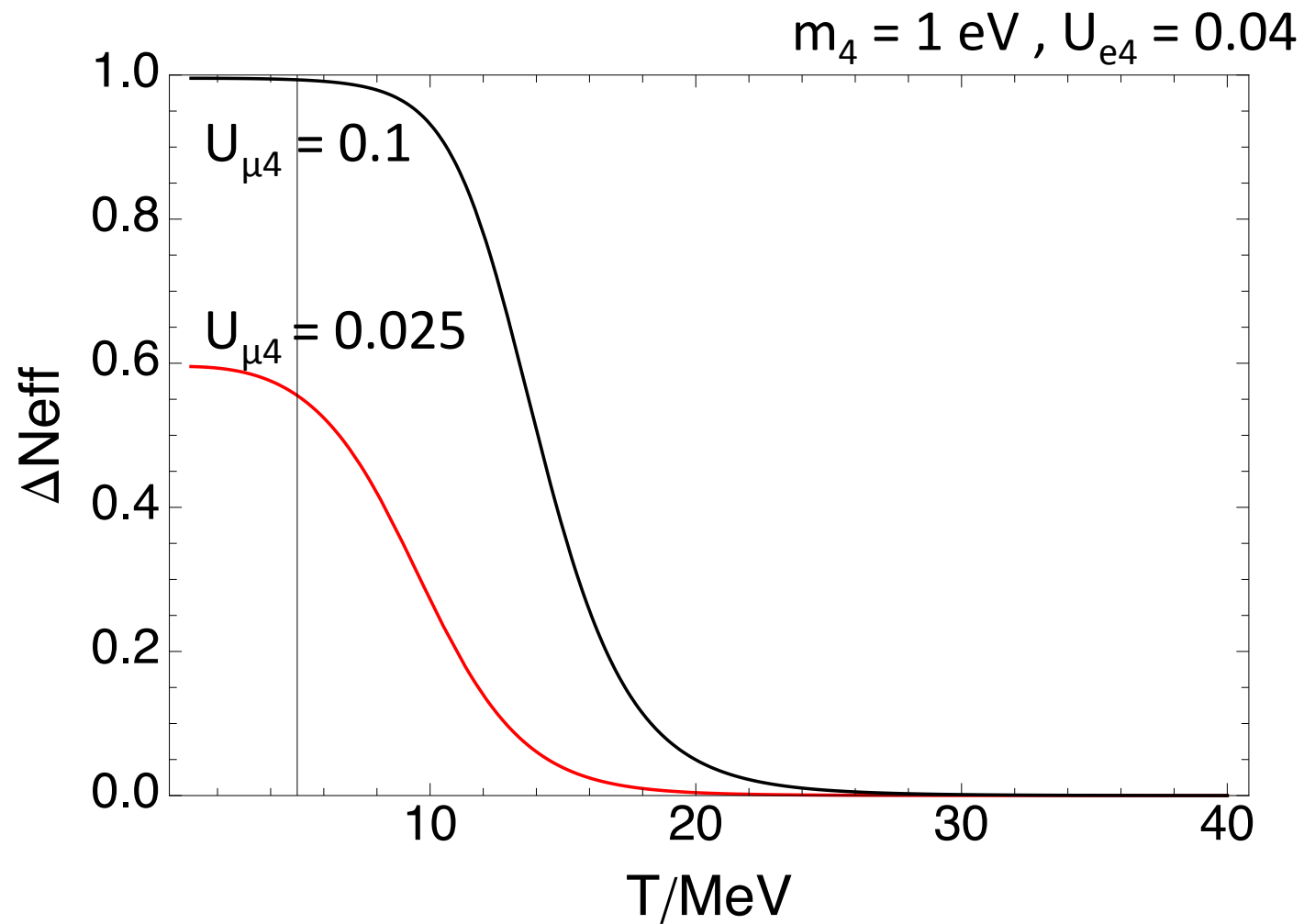
$$\Gamma = I(\Gamma_e, \Gamma_\mu, \Gamma_\tau, 0, 0)$$

$$\rho_{eq} = I \left(1 / (1 + e^{E/T}) \right)$$

– Monochromatic approximation

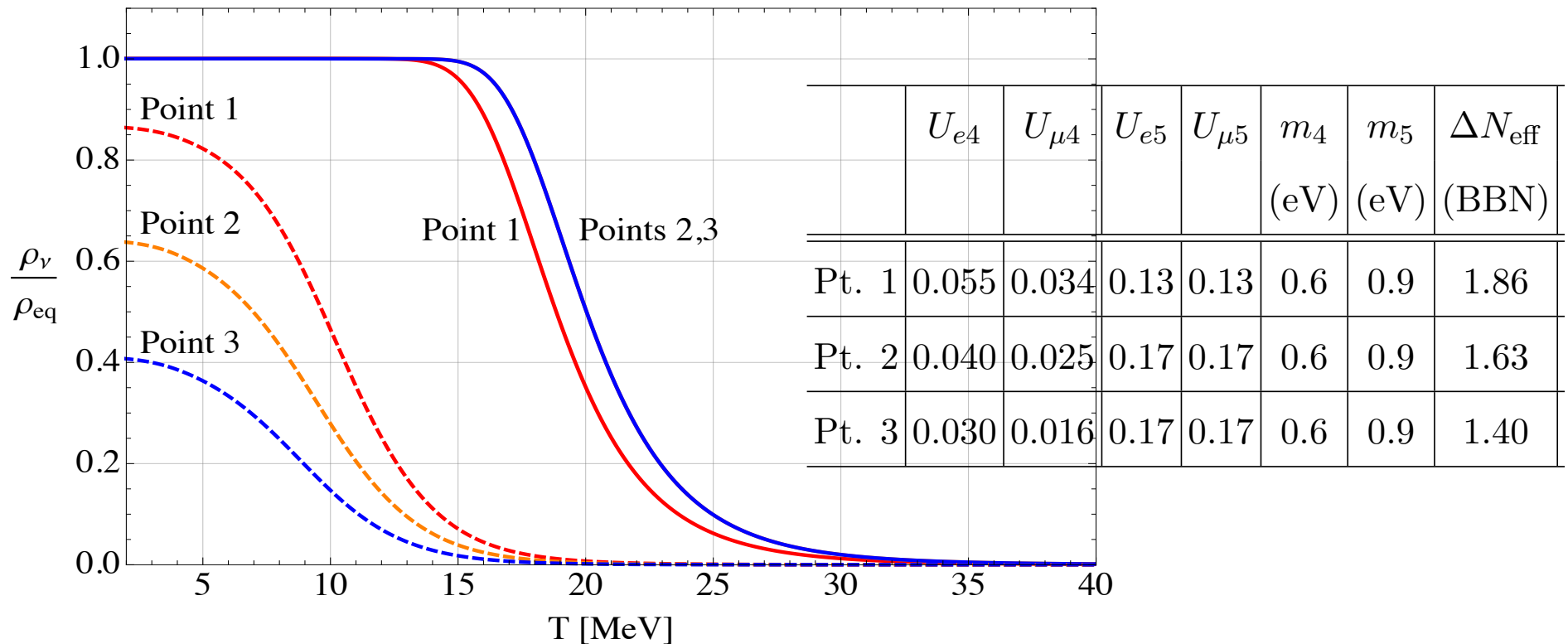
Melchiorri et al., JCAP 0901, 036 (2009)

Results: $\Delta N_{\text{eff}}^{\text{BBN}}$



$\Delta N_{\text{eff}}^{\text{BBN}}$ for 3+2

- Scan of allowed region from Giunti and Laveder, 2011
- Shown: points allowed within 2σ , giving minimum N_{eff}



Summary: ν_s at BBN

- $3 + 1$ predicts $N_{\text{eff}}^{\text{BBN}} = 4$
 - in absence of lepton asymmetry
 - Tension with cosmology?
- $3+2$ predicts $N_{\text{eff}}^{\text{BBN}} \sim 4.4 - 5$
 - Tension with cosmology

MASS SUPPRESSION

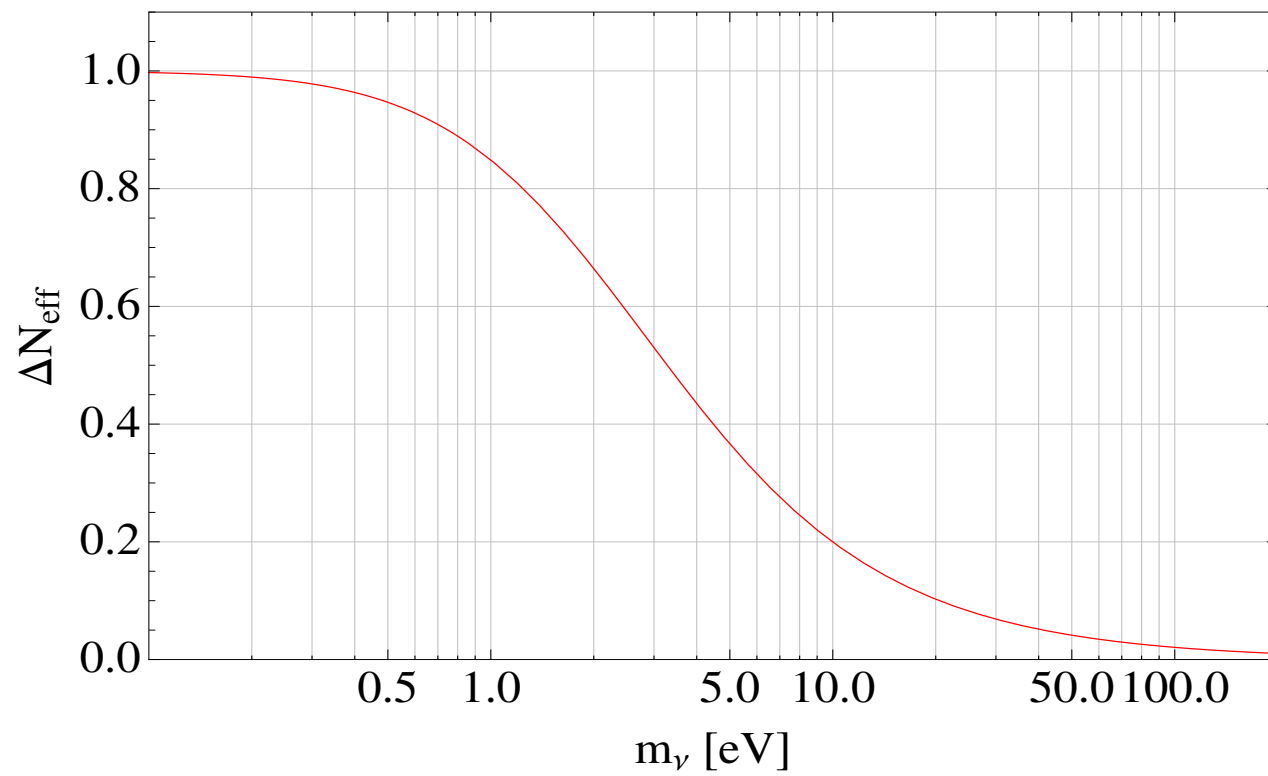
CMB: mildly relativistic ν_s

- Neutrino “temperature” at matter/radiation equality: $T_\nu \approx 0.55$ eV
 - Comparable with $m_4 \sim$ eV
- Contribution to $N_{\text{eff}}^{\text{CMB}}$ through *pressure* density
 - Mass must be included

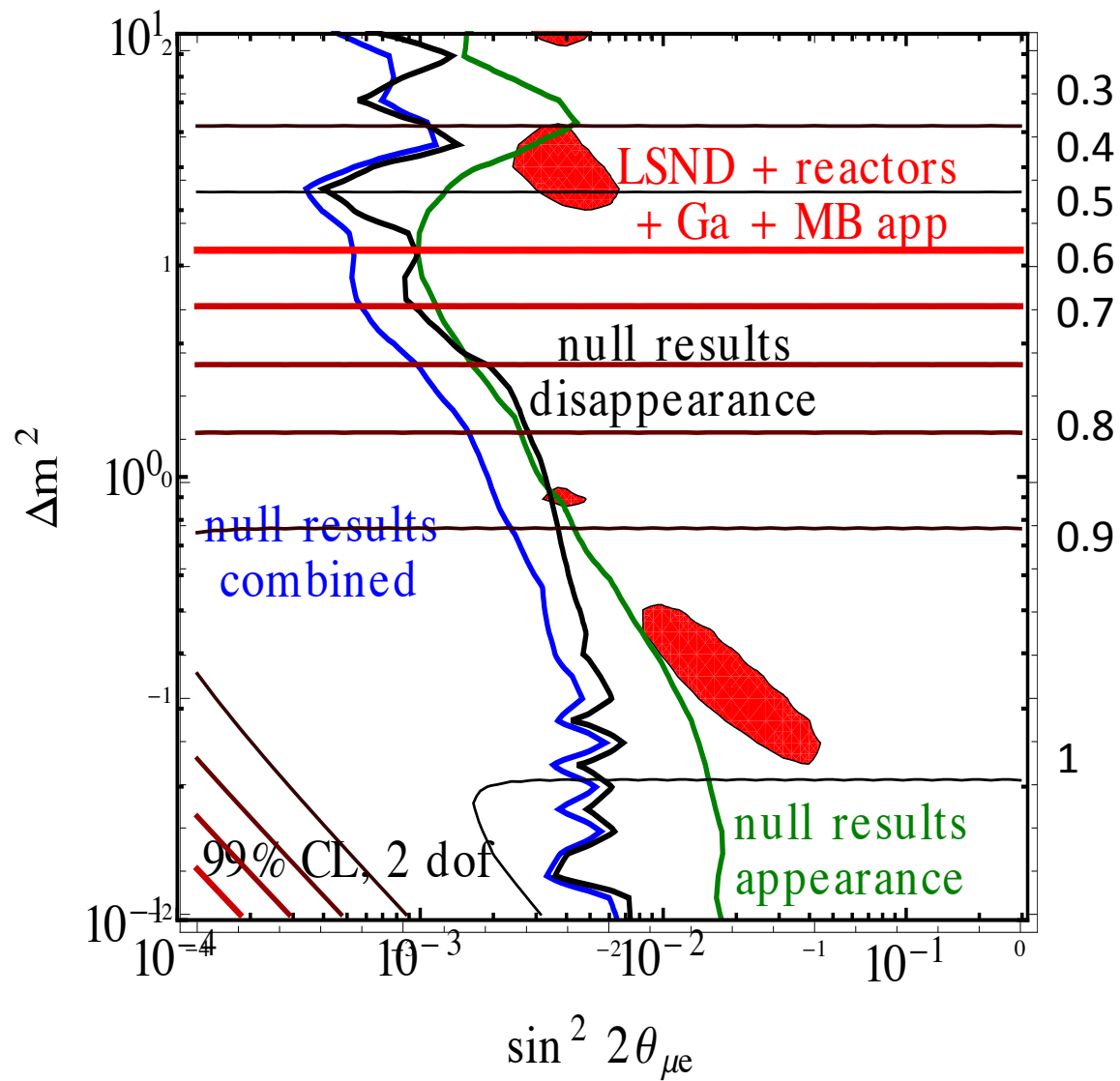
$$N_{\text{eff}} = \frac{\rho_\nu^{\text{rel}}}{\rho_{\nu, m=0}^{\text{th}}} = \frac{P_\nu}{P_{\nu, m=0}^{\text{th}}}.$$

$$P_\nu = \frac{g}{2\pi^2} \int dp \frac{p^4}{3E} f_\nu(p), \quad E = \sqrt{m^2 + p^2}.$$

- contribution of one thermalized sterile neutrino to $N_{\text{eff}}^{\text{CMB}}$



- 3+1 : iscontours of $\Delta N_{\text{eff}}^{\text{CMB}}$



ν_s and cosmological mass limit

- Constrained quantity:

$$\Sigma = m_1 + m_2 + m_3 + m_4 \times \Delta N_{\text{eff}}^{\text{BBN}}$$

- From CMB measurement of $\Omega_{m,\nu}$
- Bound (WMAP9): $\Sigma < 0.7 \text{ eV}$
 - Incomplete thermalization lessens conflict

3+2 summary

| | U_{e4} | $U_{\mu 4}$ | U_{e5} | $U_{\mu 5}$ | m_4 (eV) | m_5 (eV) | ΔN_{eff} (BBN) | ΔN_{eff} (z_{eq}) | $\sum m_{\nu_s}^{\text{eff}}$ (eV) |
|-------|----------|-------------|----------|-------------|---------------|---------------|----------------------------------|---|---------------------------------------|
| Pt. 1 | 0.055 | 0.034 | 0.13 | 0.13 | 0.6 | 0.9 | 1.86 | 1.68 | 1.31 |
| Pt. 2 | 0.040 | 0.025 | 0.17 | 0.17 | 0.6 | 0.9 | 1.63 | 1.47 | 1.18 |
| Pt. 3 | 0.030 | 0.016 | 0.17 | 0.17 | 0.6 | 0.9 | 1.40 | 1.25 | 1.05 |

DISCUSSION

Sterile neutrino(s) contribution to N_{eff}

- May be not integer
 - Incomplete thermalization
- May be different for BBN and CMB
 - Mass suppression
 - Signature of eV scale ν_s

SBL-motivated sterile neutrinos

- $3 + 1 : N_{\text{eff}}^{\text{BBN}} = 4$
 - Uncertain compatibility with dark radiation constraints
 - Some tension with cosmological mass bound
- $3 + 2 : N_{\text{eff}}^{\text{BBN}} \geq 4.4$ (or so)
 - Up to one partially populated
 - tension with dark radiation bounds
 - Conflict with cosmological mass bound

Next steps

- SBL experiments: open questions on systematics
- Ab-initio analyses desirable
- towards global analyses: *all* cosmological data + *all* terrestrial data
 - Possible? Meaningful?